



Emissions and exposure assessments of SO_X, NO_X, PM_{10/2.5} and trace metals from oil industries: A review study (2000–2018)



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ABSTRACT

Rapid urbanization and industrial growth have caused massive increase in the number and the production capacities of oil industries. Such industries release a wide-range of ambient acidic gases, particulate matters (PMs) and trace metals into the environment. They can also undergo chemical transformation and nucleation to form new chemical species and secondary aerosols. These pollutants are potentially carcinogenic and may cause cardiorespiratory, pulmonary mortalities and morbidities to the exposed population through inhalation, ingestion and dermal contact. Hence, the main objective of this review study was to identify various approaches used in monitoring, measurement, and control of ambient acidic gases, PMs and trace metals from oil industries. The review study revealed that PM_{10/2.5}, SO₂, NO₂, and trace metals were the widely reported ambient air pollutants released from oil industries. Cancer and respiratory diseases were the major health effects associated with such emissions. Air quality monitoring stations, samplers and dispersion models were found as the main approaches used to determine the emissions. Moreover, recommendations on ultrafine particles, Nano-particle and long-range transportation exposure assessments of pollutants were explored. Apart from that, the fate of pollutants, properties, routes of exposure, human health risk assessments and new approaches of emerging control technologies (Fenton and Ultrasonic reactions mainly on SO₂, NO_x and Hg reductions) were systematically reviewed. Finally, additional research on exposure assessment of oil industry emissions by private companies and government agencies was discussed.

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Abbreviations: AQDMS, air quality dispersion modeling systems; AERMOD, American Meteorological Society/US Environmental Protection Agency Regulatory Model; AQMS, air quality monitoring stations; BP, boiling point; BTU, British Thermal Unit; CALPUFF, California Puff model; CEMS, continuous emission monitoring system; COPD, chronic obstructive pulmonary disease; CI, confidence intervals; FCCU, fluidized bed catalytic cracking unit; H₂S, hydrogen sulfide; HRA, health risk assessment; HYSPLIT, hybrid-single particle lagrangian integrated model trajectory; GBD, global burden of diseases; GCC, Gulf cooperation countries; GLC, ground level concentration; ICP-MS, inductively coupled plasma-mass spectrometer; IHD, ischemic heart disease; ISCST3, industrial source complex short term, version 3; LPG, liquefied petroleum gas; LUR, land use regression; MP, melting point; MW, molecular weight; MRAD, minor restricted activity day; NO₂, nitrogen dioxide; NO_x, nitrogen oxides; PM, particulate matter; PC, physical characteristics; RAD, restricted activity day; RR, relative risk; SO₂, sulfur dioxide; SOL, solubility; TSP, total suspended particles; UFP, ultra fine particle; US EPA, United States Environmental Protection Agency; VP, vapor pressure; WHO, World Health Organization; WRF-CALPUFF, Weather Research and Forecasting California PUFF.

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1. Introduction

Oil industries play a very important role in the provision of energy and economic growth. Today, refinery and petrochemical products are consumed by numerous industries for various purposes, such as car industries, aviation sector, manufacturing industries, and electrical power generation (Ambituuni et al., 2015; Chan et al., 2017; Siddiqui et al., 2018; Varjani et al., 2017). Exploration, refinery, loading/unloading, transportation, storage of raw materials and products release different kinds of dangerous air pollutants into the environment (Cui et al., 2018; Liu et al., 2018b; Omidvarborna et al., 2018; Singh et al., 2013). According to Shtripling and Bazhenov (2015), refinery emissions are released from different steps of production line and thus, a typical oil refinery can emit about 50 different atmospheric air pollutants. In addition, other accidental activities such as spillage, venting, decommissioning and loading of products are also potential sources of gaseous emissions (Varjani et al., 2017). Among them, the most important pollutants are acidic gases (NO_2 , SO_2 , etc.), heavy metals and particulate matter (PM) emissions (Amoatey et al., 2018a, 2017; Civan et al., 2015; Laidlaw et al., 2017; Sarnela et al., 2015; Zhang et al., 2017b).

In petrochemical industries and oil refineries, most of the ambient air pollutants are emitted during combustion of fuel gas. The resulted plume contains high amount of sulfur (S) and nitrogen (N) compounds, trace metals and PMs due to the presence of enzymes and biomass within the combustible fuel (Affum, 2015; Oladimeji et al., 2015). Further, poor production and maintenance procedures could also release a significant amount of pollutants to the environment (Mastorakis and Iyer, 2009). For example, global energy sector emissions of SO_2 (including oil industries) as of 2010 were estimated to be approximately forty tera gram (~40 Tg) (Klimont et al., 2013).

Most of the trace metal pollutants emitted from oil industries are found among the top 30 designated United States Environmental Protection Agency (US EPA) urban air toxics, which are known to cause cancer and other defects in human reproductive systems (EPA, 2018c; Jia and Foran, 2013; Liu et al., 2018b; Wallace et al., 2018). Metals, such as As, Ni, Pb, Cr, Cu, etc., are among the serious air pollutants due to their easier mode of human contact. They exist in the form of aerosols in the air and can cause lung, bladder and skin cancer (Bari and Kindzierski, 2017; EPA, 2018b).

Similarly, emissions of $\text{PM}_{2.5}$ and PM_{10} from oil refineries have also attracted global concerns due to their human health effects associated with respiratory and cardiovascular mortalities and morbidities (Abdolahnejad et al., 2017; Agarwal et al., 2017; Avino et al., 2016; Balasubramanian et al., 2017; Bonyadi et al., 2016; Callen et al., 2014; Chen et al., 2017b; Dodla et al., 2017; Khaniabadi et al., 2017c; Li et al., 2018a; Marzouni et al., 2017; Michanowicz et al., 2016). Estimates from the global burden of diseases have shown a sharp increase in mortality cases of $\text{PM}_{2.5}$ exposures, ranging from 3.3 to 4.3 million for 2013 and 2015, respectively (Ostro et al., 2018). Global source attribution studies also indicated that 15 to 18% of PM emissions were due to industrial activities, where petrochemical industries were recognized as one of the major con-

tributors (Karagulian et al., 2015). According to US EPA (2018a), the ratio of $\text{PM}_{2.5}/\text{PM}_{10}$ has high potential of deposition rate into the lungs. Hence, it can readily cause pulmonary mortalities to the exposed populations, especially people who suffer from lung diseases. Considering the health effects of the aforementioned pollutants and providing the required control measures, it is important to monitor the frequency and magnitude of emissions from oil-based industries (Shtripling and Bazhenov, 2015).

The main objective of this review is firstly to identify various approaches used in monitoring, measurement, and control of ambient acidic gases, PMs and trace metals from oil industries; secondly, to assess the health risk induced by exposure to the oil-based pollutants. In addition, the new and conventional emission control strategies of the aforementioned pollutants were also discussed. Determination of transport and concentration levels of ambient acidic gases, trace metals, and PMs from oil industries can be achieved by (1) samplers, (2) air quality monitoring stations (AQMS), and air quality dispersion modeling systems (AQDMs) (Gulia et al., 2015; Rood, 2014; Zhou et al., 2014). However, each of these measurement methods has its own advantages and limitations that this review tried to highlight.

2. Research methodology

This article was prepared based on the state-of-the-art review guidelines, conventional/scientific literature approaches and grey literature procedures. Peer-reviewed research papers were reviewed in different scientific electronic resources, including Scopus, ScienceDirect, Springer, Wiley Library, PubMed and Web of Science (version 5.29). The terminologies used during the search were: ("petrochemical industries" or "oil refineries") and ("air quality" or "human health") and ("Particulate matter" or " SO_2 " or " NO_2 " or "fine particles" or " PM_{10} " or " $\text{PM}_{2.5}$ " or "heavy metals" or "trace metals") and ("mortalities", "exposure" or "cancer" or "toxicity" or "respiratory diseases" or "pulmonary diseases" or "control technologies"), while indoor air pollution papers were excluded. Documents published on the websites, including World Health Organization (WHO)/Europe and US EPA organizations were also included. The search was limited to an English based peer reviewed papers and mostly covered documents from 2000 to 2018. Since, oil industries are mostly owned by governments and private organizations, air quality studies might be published outside the peer-reviewed literature and recognized scientific databases. So, a grey literature approach based on similar keywords through Google search was also conducted on the similar keywords as mentioned above. In all, more than 150 peer reviewed published papers on both ambient pollutant emissions from oil-based and human health assessment studies were included in the study.

3. Ambient air pollutant emissions

The basic operations of most refineries involve the conversion of crude oil (the complex mixture of hydrocarbons and inorganic compounds) to consumable lower molecular weight products such as

Table 1

Properties of and toxicity effects common pollutants from petrochemical industries (Ashar, 2016; EPA, 2018b; Kim et al., 2016).

Pollutants	Physical and Chemical Properties						Interaction with Humans	
	PC	MW[g mol ⁻¹]	BP[°C]	MP[°C]	SOL [g ml ⁻¹]	VP[N m ⁻²]	Exposure Route	Health and Toxicity Effects
SO ₂	Colorless, irritating, pungent smell	64.058	−10	−75.5	107	330	Inhalation, skin, eye contact	Rhinorrhea, sore throat, difficulties in breathing, bronchoconstriction
NO ₂	Reddish brown, pungent, acidic odour	46.005	21.2	−11.2	React with Water	96	Inhalation, ingestion, eye contact	Chronic bronchitis, dyspnea, pulmonary edema, chest pains
H ₂ S	Colourless, rotten egg smell	34.076	444.6	95.3	3.74	1880	Inhalation, skin, eye contact	Respiratory, bronchitis, damage to the eye, irregular heartbeat, convulsion
C ₆ H ₆	Colourless, aromatic vapour	78.114	80	5.6	1.79	10	Inhalation	Human carcinogenic, convulsions, dizziness, damage to bone marrow, respiratory problems
Pb	Bluish, grey, soft, tarnishing	207.200	1740	327.4	Insoluble	Nil	Inhalation, ingestion, skin contact	Human carcinogenic, Anemia, lowers IQ in children, premature birth
V	Powered grey and shiny	50.941	3407	1910	Insoluble	Nil	Inhalation, ingestion	Damages to cardiovascular system. Respiratory effects, lung cancer, heart diseases
Cu	Reddish, odorless solids	63.546	2595	1083	0.00968	0.0	Inhalation, ingestion	Lung and liver diseases, irritation of upper respiratory tract
Hg	Whitish, heavy, odorless	200.592	357	−39	insoluble	0.26	Inhalation, ingestion	Affect nervous system, inflammation of the lungs, pulmonary edema, Kidney malfunction
Ni	Grey, silvered powder	56.693	2730	1455	insoluble	0.0	Inhalation, ingestion	Carcinogenic to humans, dermatitis, asthma allergies, alteration of chromosomes, renal malfunction
Cd	Silvery, blue soft metal	112.414	765	321	Insoluble	0.0	Inhalation via aerosol form	Causes cancer, bronchitis, pulmonary irritation, lung diseases, emphysema
As	Blackish in the ambient environment, grey, odorless	74.922	Nil	Nil	Insoluble	0.0	Inhalation via aerosol form, Ingestion	Causes lung cancer, lower birth weight in children, increases abortions in women, causes kidney failure
Particles	Diameter	Formation	Components	Solubility	Lifetime	Duration of Travel	Exposure Rout	Health Effects
PM _{2.5/10}	<2.5–10 um	Nucleation, Coagulation, Reactions, Fog	Nitrate, Sulfate, metals, hydrogen ion	Highly soluble, hygroscopic	More than 24-hours-weeks	100–1000s km ^{−1}	Inhalation	Impaired lungs function, aggravates asthma, heart attacks, respiratory diseases, visibility

liquefied petroleum gas (LPG), petrol, kerosene, diesel, naphtha and heavier hydrocarbon products (asphalt, lubricating oil and wax) (BAAQM, 2015; Chen et al., 2018a; Varjani et al., 2017). The production process releases enormous amount of pollutants into the environment, including inorganic acidic trace gases (Sulfur dioxide, Oxides of nitrogen, Hydrogen sulfide) particles (PM_{2.5} and PM₁₀), and various types of trace metals (Chromium (Cr), Vanadium (V), Nickel (Ni), Arsenic (As), Manganese (Mn), Cadmium (Cd), Mercury (Hg), and Lead (Pb)) (Chio et al., 2014; EPA, 2018c; McCoy et al., 2010; Moreno et al., 2008; Rodriguez-Espinosa et al., 2016; Sarnela et al., 2015; Singh et al., 2015; Thepanondh et al., 2016; Yateem et al., 2010). The characteristic of these pollutants are summarized in Table 1. Ragothaman and Anderson (2017) and BAAQM (2015) summarized the release of emissions in different steps of production:

(1) Process emissions (cracking, reforming, isomerization, etc.)

(2) Combustion process emissions (furnaces, heaters, boilers, and flares)

(3) Fugitive emissions (leakages from pipelines and storage emissions through loading/unloading, transport, etc.)

Acidic gases have low melting and boiling points and they have high solubility in water. They are also precursors (e.g., NO₂) of other harmful ambient air pollutants such as Ozone (O₃) (Liu et al., 2018a; Nuvolone et al., 2018). Whereas, trace metals have high molecular weights, high boiling and melting points with low vapor pressure showing very low solubility (or even insoluble) in water (see Table 1). They can persist in the ambient air in the form of fine aerosols (Balasubramanian et al., 2017). The transport kinematic mechanisms of trace metals are affected by their chemical and physical properties such as mass flow, molecular diffusion and dispersion. These properties tend to affect the dynamic behaviors of trace metals at different temporal and spatial timescales (Peng et al., 2018). For example, the degree of human exposure and health

impacts of these pollutants (Table 1) depend on deposition rate, distribution and residence time in the ambient environment, which are influenced by their chemical/physical properties (Li et al., 2017; Pan et al., 2017).

Ambient PM_{2.5} and PM₁₀ from oil industries apart from being hydroscopic, forming haze and consisting of several species (e.g., carbonaceous and ionic compounds), undergo long-range transports as well (Balasubramanian et al., 2017; Omidvarborna et al., 2016). In petroleum processes, most of the PM_{2.5}/PM₁₀ are emitted from the fluidized bed catalytic cracking unit (FCCU) that are made up of alumina and silica catalyst. FCCU serves as a source of PM emissions with different elemental compositions (Al, Si, Ce, etc.); however, they are not a major contributor to PM (Amoatey et al., 2017; Bozlaker et al., 2013).

4. Fate of the pollutants in the ambient environment

Reactive gaseous compounds are the potential causes of soot and aerosol formation (Li et al., 2018b). Recent studies showed that aerosols, which were emitted from oil industries could be able to (1) persist in the ambient environment for a long time, (2) transport into the indoor environment, and (3) undergo long-range of transformation and transport phenomena to a pristine ambient environment (Avino et al., 2016).

Most PMs, which are emitted from oil refineries (e.g., coke) carry high quantities of heavy metals (e.g., Pb, Cu V, Si, Ni, Zn, and As) and then become suspended in the ambient air through wind circulations (Bosco et al., 2005). According to Soriano et al. (2012), fine particulates from petrochemical sources that contained heavy metals could be transported several kilometers and then get deposited on the land and water. Settling of trace metals on the soils is primarily attributed to their heavy molecular weight (Soriano et al., 2012; Taiwo et al., 2014). Also, some PM based metals can exist in the forms of Nano and ultrafine particles (UFP), where they easily get suspended and could easily be exposed to humans through inhalation (González and Rodríguez, 2013).

Smaller aerosols can form a new critical nucleus by the process called nucleation, and then grow further to form a larger aerosol through condensation and coagulation mechanisms (Jiang and Xia, 2017; Li et al., 2018b; Omidvarborna et al., 2015). Further, according to Balasubramanian et al. (2017), secondary aerosols could be formed as a result of photochemical reactions between certain ions and precursor gaseous compounds in the air. In the presence of unfavorable meteorological factors in the ambient environment (especially fluctuations in relative humidity), aerosol concentrations could be increased. On other hand, emissions of trace gases (mostly NO_x, SO_x, NH₃, etc.) could also form aerosols by undergoing particle formation, coagulation and transportation to form ionic species (sulfate and nitrates) and fine particulates (Omidvarborna et al., 2015; Stoffregen et al., 2017). Sudalima et al. (2015), reported that the atmospheric deposition of NO₂ and SO₂ aerosols of an oil refinery resulted in 27.1% and 58.0% of nitrates and sulfate concentrations in the rainwater, respectively.

Although evaluating the fate of the pollutants in the ambient environment is a challenging task, it is counted as a mandatory part of measuring the associated risks. However, field data obtained from on-site monitoring are always needed for any environmental fate and exposure studies, which result in reliable information about the humans and the environment exposure to pollutants from the industries.

5. Exposure routes

The ambient air pollutants get into human body through inhalation (respiratory pathways), dermal contact (skin contact), and

ingestion (food consumption) (Varjani et al., 2017). Although humans can be exposed to the air pollutants via all the above routes, the easiest route of entry of the pollutants (e.g., acidic gases, trace metals and PMs) to human body is through inhalation. For example, Smargiassi et al. (2014), reported that children living near petrochemical complex faced pulmonary and cardiovascular diseases, especially asthma, due to respirable SO₂, NO₂ and PM_{2.5} emissions from the facility. Harari et al. (2016) reported that oil refineries were one of the important sources of heavy metals emissions (such as Ni), which could impact humans via inhalation and dermal contact. It should be noted that humans do not have much control to physically filter the inhale air but it can be feasible for other routes such as dermal contact or ingestion. Human and ecosystem exposure to these ambient air pollutants can be reduced if process, storage and transportation operations are managed efficiently. The routes of exposure to the specific pollutants are indicated in Table 1. Inhalation and ingestion are the major exposure routes of common air pollutants from petrochemical industries; however, skin and eye contact have been also reported in case of sulfur compounds. Common health and toxicity effects with respect to such pollutants are summarized in Table 1, which are either carcinogenic or cause major difficulties to humans.

Increasing in economic activities and infrastructural developments through rapid rural-urban transitions has increased fossil fuel production (mainly crude oil) and consumption, irrespective of the various attempts to promote renewable energies technologies (e.g., biofuel, solar and wind energy) (Alipour et al., 2017; Asif, 2016; Atalay et al., 2016; Mondal et al., 2016). Table 2 provides a summary of annual importation/exportation of various oil-based products in different countries. Although, the petroleum production may meet the global energy demands to accelerate economic growth; emissions, which include most criteria air pollutants (SO₂, NO₂, and PM), can greatly affect human health systems and properties. Exposure to NO₂ for about 30–60 minutes causes chronic lung inflation and aggravates respiratory symptoms among asthmatic population groups (Hadidi et al., 2016). Studies have shown that petroleum refinery could release high amount of UFP (25,000–95,000 cm³ of PM_{0.1}), which are currently unregulated globally compared to vehicular emissions (5000 – 25,000 cm³ of PM_{0.1}) (González and Rodríguez, 2013). Such ambient emissions from petroleum refineries can be reduced if alternative green energies and sustainable development agenda are prioritized (Xu and Hao, 2017).

6. Monitoring and estimation of the pollutants

Determining the extent of human and ecosystem damages from oil industries depends on the rigorous methods of monitoring and assessing of the ambient pollutant emissions (Kampa and Castanas, 2008; MacIntosh et al., 2010; Morra et al., 2009). The traditional method of measuring the pollutants has been limited to the application of samplers (Callen et al., 2014; Chen et al., 2017a; Lang et al., 2017; Misawa et al., 2017; Sosa et al., 2017). This method has several limitations, such as (1) it cannot measure emissions continuously, (2) it has low spatial coverage, (3) it cannot perform long-term measurements, and (4) it is expensive and labor intensive approach (Melymuk et al., 2011; Mittal et al., 2013; Ramos et al., 2018; Schindler et al., 2016; Yusa et al., 2009). Due to these limitations, AQMS has offered an opportunity to fill the gaps as it can simultaneously measure several types of air pollutants with high temporal and spatial coverage. Such specifications, making AQMS as a preferred instrument in measuring several pollutants from oil industries (Khan et al., 2017; Wu et al., 2015; Xiao et al., 2018; Zhang et al., 2013). However, measurement of ambient pollutants from oil industries with AQMS may not be the best approach due to infiltration and impact by similar pollutants from other sources

Table 2Annual Petroleum production (both importation and exportation) (10^3 tons) of the selected countries and the World (IEA, 2015).

Country/Region	Crude oil (Imports;Exports)	LPG (Imports;Exports)	Gasoline (Imports;Exports)	Diesel (Imports;Exports)
Oman	48,067 (0;- 41,356)	323 (0;-422)	2974 (0;-50)	2963 (0;-436)
Qatar	31,915 (0;-28,216)	333 (0;-9152)	1583 (0;- 162)	2091 (602;-2906)
UAE	148,838 (0;-124,538)	1001 (39;-7361)	4931 (3187;-851)	9194 (2350;-5455)
Kuwait	144,908 (0;-99,554)	153 (0;-7844)	3175 (0;-91)	10,294 (0;- 6650)
Bahrain	10,049 (3308;0)	63 (0;-223)	818 (0;-4)	4080 (0;-3765)
KSA	508,027 (0;-368,477)	1445 (0;-20,293)	21,090 (9431;-6716)	47,114 (12,207;-19,594)
GCC(Total production)	891,804	3318	34,571	75,736
USA	464,394 (363,163;-22,938)	7105 (4480;-21,576)	349,844 (31,117;-26,435)	241,401 (10,998;-57,520)
Canada	154,620 (44,743;-131,780)	1284 (123;-356)	30,167 (2887;-7155)	30,136 (1627;-6725)
UK	42,826 (42,672;-29,965)	2208 (797;-814)	17,024 (3798;-10,338)	20,687 (14,440;-4599)
Australia	15,382 (19,076;-11,404)	509 (491;-1151)	9403 (4046;-87)	9514 (12,523;- 45)
France	835 (56,742;-40)	1561 (3330;-1150)	11,119 (491;-4098)	25,304 (23,832;-2783)
Germany	2414 (91,275;-333)	2656 (732;-259)	18,945 (1911;-4421)	43,520 (18,364;-8279)
Norway	78,066 (1151;-64,962)	1087 (250;-5617)	3988 (239;-2785)	6503 (1695;-3340)
Italy	5470 (62,457;-709)	1299 (2262;-236)	15,790 (502;-8532)	31,996 (3010;-8923)
Spain	232 (64,628;0)	1699 (780;-395)	9105 (103;-4741)	27,467 (4642;-5400)
Africa	366,692 (35,346;-305,230)	2229 (6650;-8167)	16,553 (26,872;-1640)	31,326 (47,347;-2056)
Asia*	151,887 (380,729;-51,965)	14,235 (18,486;-3005)	82,640 (50,416;-44,042)	186,241 (51,928;-66,723)
China	214,556 (335,483;-2866)	25,229 (12,440;-1442)	121,033 (170;-1442)	178,246 (428;-7163)
EU	68,089 (553,434;-36,430)	16,054 (21,040;-7758)	118,943 (27,300;-80,793))	256,548 (127,538;-103,803)
Global	3,877,112 (2,168,736;-2,100,901)	109,751 (97,017;-103,489)	975,332 (204,565;-208,799)	1,350,844 (362,604;-374,973)

* Not including China.

(transportation, traffic, constructions) (Brand et al., 2016; Chen et al., 2018b; González and Rodríguez, 2013; Pedroso et al., 2016). Additionally, continuous emission monitoring system (CEMS) is a very important instrument that determines real-time emission rates or flow rates of different pollutants, especially SO₂, NOx, and PM from stationary sources.

CEMS data of a typical oil refinery showed that the default PM₁₀ and PM_{2.5} emission values for the production of 50,000 barrels of crude oil were 208 tons yr⁻¹ and 189.5 tons yr⁻¹, respectively (EPA, 2011). According to CEMS measurements, for a continuous refinery combustion operation, 3.5 tons yr⁻¹ of SO₂ and 940 tons yr⁻¹ of NOx were emitted to the ambient environment for 150×10^6 British thermal units (Btu) per hour burning of refinery fuel gas (EPA, 2011). The mean emission factor for Cd, Hg, Ni and Pb in pounds per million British thermal units (lb MMBtu⁻¹) were 2.38×10^{-3} , 3.23×10^{-4} , 5.59×10^{-3} and 2.42×10^{-3} , respectively (EPA, 2011). The emissions of these pollutants in cities, regional and global levels can be estimated according to the data shown in Table 2. Based on the emission factors, the contribution of Ni compared to the other elements is predominant (Harari et al., 2016). Additionally, psychological problems of the exposed population could be due to spillage of petroleum products (Ramirez et al., 2017).

In recent years, several AQDMs have been used as efficient and cost-effective means of determining temporal and spatial pollutant emissions from different industries. AQDMs are considered as pre-

ferred models as they could simulate air pollutants from emission sources at ground level concentrations (Amoatey et al., 2018a). The common AQDMs are Industrial Source Complex Short Term (ISCST) (Abdul-Wahab et al., 2008), California Puff model (CALPUFF) (Lang et al., 2017; MacIntosh et al., 2010; Rood, 2014), American Meteorological Society/US Environmental Protection Agency Regulatory Model (AERMOD) (Chen and Carter, 2017c; Michanowicz et al., 2016) and Hybrid-Single Particle Lagrangian Integrated Model Trajectory (HYSPLIT) (Dodla et al., 2017). The basic data required in estimating pollutants with these models include emission rates, stack data (height, diameter and temperature), local meteorological information (ambient temperature, wind speed and direction, sensible heat flux, and convective layer), and land use characteristic data (elevation, albedo, etc.) (Abu-Eishah et al., 2014; Amoatey et al., 2018a, 2017). The measurement instruments such as passive samplers, AQMS, and CEMS could be modified to measure/validate pollutants from oil industry emissions compared to AQDMs.

Amoatey et al. (2018a) reported that employing AQDMs in assessing ambient concentrations of SO₂ and NO₂ emissions from an oil refinery within a residential location could be very beneficial in assessing future health risk assessment (HRA) of the residents due to the reliability of the model. Comprehensive data about several ambient measurement procedures and their associated measured pollutants from the selected oil industries are shown in Table 3. The table contains wide variety of pollutants,

Table 3

Ambient pollutants emission from selected oil industries in different countries.

Study Location	Industry Unit	HRA	Instrument/ Model Used	Pollutants Emitted (GLC ^a)	References
Fahaheel, Kuwait	Ahmadi	No	AERMOD	SO ₂ (2.5×10^{-4}) ppm NO (1.64×10^{-6}) ppm	AL-Haddad et al. (2012)
Umm Alhyman, Kuwait	Shuaiba	No	AERMOD	SO ₂ (1.52×10^{-4}) ppm NO (4.37×10^{-4}) ppm	AL-Haddad et al. (2012)
Al Sahil, UAE	ADGAS ^b	No	AERMOD	24 h SO ₂ ($124.9 \mu\text{g m}^{-3}$)	Abu-Eishah et al. (2014)
Sailing Club, UAE	ADGAS	No	AERMOD	24 h SO ₂ ($111.06 \mu\text{g m}^{-3}$)	Abu-Eishah et al. (2014)
Al Jimi, UAE	ADGAS	No	AERMOD	24 h SO ₂ ($194.92 \mu\text{g m}^{-3}$)	Abu-Eishah et al. (2014)
Montreal, Canada	Nil	Yes	Ogawa samplers	24 h NO ₂ (6.33 ppb) 24 h PM _{2.5} ($9.6 \mu\text{g m}^{-3}$) Annual PM _{2.5} (177.37 ton) Annual SO ₂ (2327.23 ton) Annual NO ₂ (773.0 ton)	Smargiassi et al. (2014)
Quebec Provinces	Nil	Yes	Monitoring stations	Annual SO ₂ (577.79 ton) Annual NO ₂ (164.34 ton)	Brand et al. (2016)
British Columbia	Nil	Yes	Monitoring stations	24 h SO ₂ (24 ppb) 24 h SO ₂ (4.5 ppb)	Brand et al. (2016)
Taiwan	Petro-AQS	No	AQMS		Chen et al. (2018b)
Dacheng, Taiwan	No.6 Naptha cracking complex	Yes	Urinary Biomarker application and ICP-MS	As ($103.76 \mu\text{g g}^{-1}$) Ni ($6.88 \mu\text{g g}^{-1}$) Pb ($1.54 \mu\text{g g}^{-1}$) Hg ($1.38 \mu\text{g g}^{-1}$) Cr ($1.94 \mu\text{g g}^{-1}$) Cu ($9.97 \mu\text{g g}^{-1}$) Cd ($0.8 \mu\text{g g}^{-1}$) V ($0.49 \mu\text{g g}^{-1}$)	Chen et al. (2018a)
Zhutang, Taiwan	No.6 Naptha cracking complex	Yes	Urinary Biomarker application and ICP-MS	Sr ($140.76 \mu\text{g g}^{-1}$) Mn ($3.52 \mu\text{g g}^{-1}$) Hg ($1.38 \mu\text{g g}^{-1}$) Pb ($1.67 \mu\text{g g}^{-1}$)	Chen et al. (2018a)
Taisi, Taiwan	No.6 Naptha cracking complex	Yes	Urinary Biomarker application and ICP-MS	As (7.5 ng m^{-3}) V (2.23 ng m^{-3})	Chen et al. (2018a)
Taishi, Taiwan	No.6 Naptha cracking complex	No	192 PM ₁₀ filters, ISC3	PM _{2.5} ($30.1 \mu\text{g m}^{-3}$) Mn (7.01 ng m^{-3})	Chio et al. (2014)
Taishi-Yulin County, Taiwan	No.6 Naptha cracking complex	No	Monitoring stations, ICP-MS	1 h NO ₂ (46.1 ppb) 1 h NO ($6.4 \mu\text{g m}^{-3}$)	Chuang et al. (2018)
Beijing, China	Nil	No	Vacuum 3 L-Summa Canister Sampler	24 h SO ₂ ($88 \mu\text{g m}^{-3}$) 24 h NO ₂ ($9.6 \mu\text{g m}^{-3}$)	Wei et al. (2014)
Tema, Ghana	Tema Oil Refinery	No	CALPUFF	24 h PM _{2.5} ($38.8 \mu\text{g m}^{-3}$) Annual PM _{2.5} ($12.6 \mu\text{g m}^{-3}$)	Amoatey et al. (2018a)
Tema, Ghana	Tema Oil Refinery	Yes	AERMOD	24 h PM _{2.5} ($38.8 \mu\text{g m}^{-3}$) Annual PM _{2.5} ($12.6 \mu\text{g m}^{-3}$)	Amoatey et al. (2017)
Aliaga Region, Turkey	Nil	Yes	Passive sampler	24 h SO ₂ ($21.1 \mu\text{g m}^{-3}$) 24 h NO ₂ ($17.8 \mu\text{g m}^{-3}$)	Civan et al. (2015)
Algeciras and La Linea, Spain	San Roque Refinery complex	No	Cascade impactor sampler	Cr ($962 \mu\text{g m}^{-3}$), Zn ($225 \mu\text{g m}^{-3}$) V ($638 \mu\text{g m}^{-3}$), Ni ($3295 \mu\text{g m}^{-3}$) Mo ($91 \mu\text{g m}^{-3}$), Co ($94 \mu\text{g m}^{-3}$)	de la Campa et al. (2011)
Santa Cruz de Tenerife	Nil	No	Ultrafine Condensation and Optical Particle Counter, Monitoring station	SO ₂ ($10 \mu\text{g m}^{-3}$), NO ($56 \mu\text{g m}^{-3}$), BC (1035 ng m^{-3}), PM ₁₀ ($26 \mu\text{g m}^{-3}$), PM _{2.5} ($13 \mu\text{g m}^{-3}$)	González and Rodríguez (2013)
Asaluyeh, Iran	South Pars Complex	No	AERMOD	1 h NO ($700 \mu\text{g m}^{-3}$)	Jafarigol et al. (2015)
Faheel and Al-Riqa, Kuwait	Mina Abdullah Refinery	No	Mobil Air Monitoring Lab	PM ₁₀ (297 ppb), NO _x (21 ppb) H ₂ S (14 ppb), NO ₂ (12.2 ppb)	Khanfar (2015)
Ustan, Korea	Ulsan Petrochemical Industrial Complex, On-San Industrial Complex	No	WRF-CALPUFF	24 h PM ₁₀ ($157.7 \mu\text{g m}^{-3}$)	Lee et al. (2014)
La Linea and Puente Maryoga, Spain	CEPSA Oil Refinery	No	PM ₁₀ Sampler	24 h PM ₁₀ ($31 \mu\text{g m}^{-3}$)	Li et al. (2018a)
Asaluyeh, Iran	Nil	No	AERMOD	Annual NO ₂ ($217.4 \mu\text{g m}^{-3}$)	Minabi (2017)
Sao Paulo ^b , Brazil	Nil	No	Monitoring station	Hourly PM ₁₀ ($785 \mu\text{g m}^{-3}$)	Nakazato et al. (2015)
Cubatao ^c , Brazil	Nil	N/A	Monitoring station	24 h NO ₂ ($37.3 \mu\text{g m}^{-3}$), SO ₂ ($11 \mu\text{g m}^{-3}$), PM ₁₀ ($37 \mu\text{g m}^{-3}$)	Pedroso et al. (2016)
Altamira, Mexico	Nil	No	PM ₁₀ Sampler	24 h PM ₁₀ ($92 \mu\text{g m}^{-3}$)	Rodriguez-Espinosa et al. (2016)
Thailand	Nil	No	AERMOD	1 h SO ₂ ($359 \mu\text{g m}^{-3}$)	Thepanondh et al. (2016)
Thailand	Nil	No	CALPUFF	1 h SO ₂ ($456 \mu\text{g m}^{-3}$)	Thepanondh et al. (2016)
Argentina	Nil	No	TOEM monitors	24 h PM ₁₀ ($50.7 \mu\text{g m}^{-3}$)	Singh et al. (2015)
Chikun, Nigeria	Kaduna oil refinery and petrochemical complex	No	ISCST3	24 h PM ₁₀ ($0.4 \mu\text{g m}^{-3}$) 24 h SO ₂ ($82.7 \mu\text{g m}^{-3}$) 24 h NO _x ($164.1 \mu\text{g m}^{-3}$)	Oladimeji et al. (2015)
Eleme, Nigeria	Port Harcourt Refining Company (I and II)	No	ISCST3	24 h PM ₁₀ ($0.45 \mu\text{g m}^{-3}$) 24 h SO ₂ ($69.1 \mu\text{g m}^{-3}$) 24 h NO _x ($1855.25 \mu\text{g m}^{-3}$)	Oladimeji et al. (2015)
Warri, Nigeria	Warri refining and petrochemical company	No	ISCST3	24 h PM ₁₀ ($1.7 \mu\text{g m}^{-3}$) 24 h SO ₂ ($444.4 \mu\text{g m}^{-3}$) 24 h NO _x ($2145.8 \mu\text{g m}^{-3}$)	Oladimeji et al. (2015)

^aGLC is the major concern for practical environmental and health assessment studies.^bADGAS: Abu Dhabi Gas Liquefaction Company.^cReceptor: Agricultural field.^dReceptor: Forest.

which are classified by US EPA (2018b) and European Commission (2016) as human carcinogenic. The major results from the table are: 1) NO emission as a primary ambient pollutant, is less considered in the research studies. According to Wu et al. (2019), NO is the main component of NOx in combustion flue gas (95 Vol.% NOx), which plays a critical role in the atmospheric environment research, and 2) many of the high capacity refineries that can emit these pollutants are located in countries such as Saudi Arabia, Iran, Russia, Nigeria, China, and Venezuela, whereas most of the pollutants are not properly monitored and regulated; thereby, they may be exceeded most of the international and global standards (Hadidi et al., 2016).

7. Human HRA of the oil-based pollutants

Exposure to the ambient pollutions from oil industries can lead to prevalence of diseases, morbidity, mortalities and restricted activity days (RADs) (Ancona et al., 2015; HRAPIE/Europe, 2013; WHO, 2018). Hence, it is important to monitor the health effects of these pollutants since they can aggravate the health conditions of the vulnerable populations (asthmatic patients, children), even upon meeting regulatory standards (Smargiassi et al., 2014).

There is a wide-range of cancer, cardiopulmonary, and respiratory diseases that have resulted from oil-industry emissions (Chiang et al., 2016; Singh et al., 2015; Yuan et al., 2016, P. Yuan et al., 2018; T.-H. Yuan et al., 2018). According to WHO/Europe (2018), there could be economic benefits of reducing ambient air pollutants (SO₂, NO₂, PM_{2.5}, and PM₁₀) exposures, especially if the human exposure levels were set to be less than 10 µg m⁻³. According to Castro et al. (2017), reducing exposure of PM₁₀ to 3.3 µg m⁻³ could prevent 36 premature deaths, 215 hospitalization days from cardiorespiratory diseases, and 47,000 restricted activity days, which would be equal to 36 million Swiss Franc per year. Table 4 reports various health effects due to ambient oil industries from selected locations across the world, including the HRA models and pollutants of interest. The human HRA models (Table 4) could better be improved to ensure accurate estimates of health effects from oil industry emissions. Because, these models were originally developed to suit urban areas with multiple ambient pollutants compared to point sources (oil refinery and petrochemical industries).

Modeling the global burden of diseases from exposure to oil industry emissions together with life cycle assessments and health impact assessments is important in understanding the overall degree of health effects from oil industries in comparison to conventional urban emissions (Gibson et al., 2013; Morsali, 2018). Also, occupational exposures due to indoor emissions including cofounders at every stage of a process needs to be explored as they are essential in designing mitigation measures to protect human health (Amoatey et al., 2018b; Clifford et al., 2018; Morawska et al., 2008).

7.1. Carcinogenic diseases

Emissions of acidic gases, trace metals and PMs from oil industries are known to be human carcinogenic as they can bind and alter the DNA of humans. Various studies have showed that ambient air pollutants from oil industries could result in several forms of cancerous diseases even when concentration levels met the air quality guidelines (Amoatey et al., 2017; Lin et al., 2017; WHO/Europe, 2017). Table 5 summarizes various international air quality guidelines for major air pollutants. A very important set-back of ambient air quality guidelines with reference to oil industries is that countries (mostly developing countries) involve with the activities of oil production do not have their own guidelines (Abdul-Wahab et al.,

2015). This may lead to a wide range of uncertainties in determining the safe levels of emissions as the international standards may not be applicable to individual country-specific emissions. Most ambient air pollutants listed in Table 3 far exceed these international guidelines, thereby showing an evidence of incidence of various mortalities and morbidities cases to the exposed population. For example, 124 µg m⁻³ of SO₂, 30 µg m⁻³ of PM_{2.5} and 1855 µg m⁻³ of NOx (Table 3) far exceed the 24-hour threshold limits of many international guidelines. Koh et al. (2014) investigated the oral and pharyngeal cancer incidence among workers from petrochemical complex in Korea. Acute leukemia in France (Pascal et al., 2013), bronchus cancer in USA (Caruso et al., 2015), lung cancer in Italy (Parodi et al., 2005) and Lymphohematopoietic cancer mortalities in Korea (Koh et al., 2011) have been reported due to emissions from Petrochemicals industries. Although various ambient air pollutants from refineries and petrochemical industries may meet local and international air quality threshold limits, they may still induce health effects among the exposed populations (Liu et al., 2016).

7.2. Cardiorespiratory mortalities

Extensive studies on cardiovascular and respiratory mortalities from acidic gases, trace metals and PM_{2.5}/PM₁₀ emissions have not been carried out from oil industries. However, several studies explored the relationship between SO₂, NO₂, PM_{2.5}/PM₁₀ exposures from the urban ambient environment and cardiorespiratory mortalities for concentrations above 10 µg m⁻³ at 95% confidence intervals (95% CI) (Honda et al., 2017; Kampa and Castanas, 2008; Maji et al., 2018; Marzouni et al., 2017). Goudarzi et al. (2017) employed WHO's recommended AirQ_{2.2.3} model to estimate cardiorespiratory mortalities from ambient PM₁₀ exposures. It was revealed that if PM₁₀ levels were reduced to 10 µg m⁻³, 184 and 476 cases of cardiovascular and respiratory deaths per pollutants could be avoided, respectively. Similarly, for 10 µg m⁻³ increase in exposure levels of SO₂, the risk of 3.4% (95% CI: 0.78–5.0%) for cardiovascular mortality and 4.2% (95% CI: 2.5–5.7%) for respiratory mortalities could occur (Khaniabadi et al., 2017d). Asl et al. (2018) estimated the attributable proportion of deaths of 4.42% (PM_{2.5}) and 1.74% (NO₂) with 95% of CI for concentrations exceeding 10 µg m⁻³. These health effects are similar to trace metals as they also occur in the form of particulates (PM₁₀, PM_{2.5}) and total suspended particles (TSP) (Chen et al., 2017b; Chio et al., 2014; Du and Turner, 2015).

The importance of SO₂, NO₂, PM_{2.5}/PM₁₀ emissions on cardiorespiratory mortalities were highlighted. However, special attentions on oil industries emissions can provide a better understanding about the short and long-term health effects associated with cardiorespiratory mortalities of peoples living nearby such industries.

7.3. Cardiopulmonary mortalities

Long and short-term exposure to acidic gases and PM_{2.5}/PM₁₀ has been associated with chronic obstructive pulmonary disease (COPD) and ischemic heart disease (IHD) related mortalities in adult populations of 30+ years (Afonso et al., 2011; Al-Hemoud et al., 2018; Forouzanfar et al., 2012; Koman and Mancuso, 2017; WHO, 2006). Yet, there are limited studies on COPD and IHD among the exposed populations living around oil refineries and petrochemical industries.

Most studies with respect to emissions from oil industries have focused on the urban environments. For example, the annual average concentration of 51.33 µg m⁻³ for ambient SO₂ exposures could increase the risk by 2.7% (95% CI: 1.1–4.2%) for myocardial infarction (Khaniabadi et al., 2017a). Premature deaths due to PM_{2.5} expo-

Table 4

HRA studies of some selected locations of close to oil-based industries.

Study Location	Pollutant(s) Emitted	Model Used	Health End Effects	Outcome	References
Mailio, Taiwan	As, Cd, Hg, Pb, V	Poisson regression	Cancer	1.29 (95% CI:0.99-1.69) of cancer risk. Elderly and females posed higher risk	P. Yuan et al., 2018; T.-H. Yuan et al., 2018
Taishi, Mailo, Dongshih, Taiwan	SO ₂	Kaplan-Meire method	allergic rhinitis bronchitis asthma	Incidence risk of 26.9 (95% CI:35.7-41.7) for allergic rhinitis 8.3 (95% CI:8.8-10.2) for bronchitis 18.5 (95% CI:25-26.9) for asthma	Chiang et al. (2016)
Mailio, Taiwan	Vanadium and 1-Hydroxypyrene	Metabolic profiling	Metabolome perturbation	40 fold exposure for Vanadium 20 fold exposure for 1-Hydroxypyrene	Yuan et al. (2016)
Taishi, Thailand	PM _{2.5}	K-means clustering model	Lactate dehydrogenase (LDH), 8-isoprostanate	High correlation exist between LHD and PM _{2.5} containing Pb, 8-isoprostanate was correlated with Pb and Se	Chuang et al. (2018)
Bangkok, Thailand	Benzene	Biomarker	Cancer	The exposed resident population may have higher risk of developing carcinogenic diseases compared to the controlled population	Kampeerawipakorn et al. (2017)
Tarragona, Spain	PAHs, SO ₂ , NO ₂ , PM _{2.5}	Multivariable analysis Lung function measurement	Asthma, Respiratory symptoms and Lung function	Higher prevalence of asthma in children and adolescence living close to the oil refinery	Rovira et al. (2014)
Yunlin, Taiwan	V, Ni, Cu, As, Cd, Hg and 1-Hydroxypyrene	Kriging models	Oxidative stress, allergic and respiratory diseases	There was an established link between chronic respiratory diseases and multiple exposure of pollutants by the subjects from the sources	Chen et al. (2017)
Taisi, Dachen, Zhutan Taiwan	V, Ni, Cu, As, Cd, Mn, Ti	Poisson Regression	Cancer	Cancer rate was about 2.43-2.55 higher among the exposed residents	Chen et al. (2018a)
Quebec and British Columbia, Canada	SO ₂ , NO ₂ , PM _{2.5}	Conditional Logistic Regression	Hospital admissions for asthma and bronchiolitis	Hospital admissions among children were associated with the emissions from the petrochemical complex	Brand et al. (2016)
Montreal, Canada	SO ₂ , NO ₂ , PM _{2.5} , Benzene, PAHs	Linear Mixed Models	Pulmonary and Cardiovascular Functions	No significant associations was found between cardiopulmonary effects and pollutants exposures	Smargiassi et al. (2014)
Malagrotta, Italy	SO ₂	Cox Regression	Laryngeal cancer, respiratory mortality and respiratory hospital admissions	Hazard Ration: 4.99% (95% CI: 1.64-15.9) for cancer mortalities and 1.13 (95% CI: 1.01-1.27) for respiratory morbidity	Ancona et al. (2015)
Tema, Ghana	PM _{2.5}	USEPA HRA Models	Lung cancer and cardiopulmonary diseases	Total of 205 deaths from cardiopulmonary and 153 mortalities from lung cancer could occur from PM _{2.5} exposure	Amoatey et al. (2017)
Falconara, Italy	SO _x , NO ₂ , Benzene	Conditional Logistic Regression	Hematological Malignancies	There is an increase in risk of Hematological Malignancies mortalities in females	Micheli et al. (2014)

Table 5

International Guidelines of some selected ambient air pollutants.

Pollutants	WHO (WHO, 2005) [$\mu\text{g m}^{-3}$]		EU (WHO/Europe, 2017) [$\mu\text{g m}^{-3}$]		US (EPA, 2015) [$\mu\text{g m}^{-3}$]	
	24-h	Annual	24-h	Annual	24-h	Annual
SO ₂	20	NA	NA	NA	197	NA
H ₂ S	NA	NA	150	NA	NA	NA
NO ₂	200	40	150	NA	NA	100
PM ₁₀	50	20	NA	NA	150	NA
PM _{2.5}	25	10	NA	NA	35	12
Pb	NA	NA	NA	0-1	0.15 ^b	NA
Hg	NA	NA	NA	1	NA	NA
Mn	NA	NA	NA	1	NA	NA
V	NA	NA	NA	1	NA	NA
Cd	NA	NA	NA	10-20 ^a	NA	NA

^a ng m⁻³.^b Three-month average.

sure might have contributed to 12,520 (10,240–15,930) deaths at 50% CI, where the concentrations were above 10 $\mu\text{g m}^{-3}$ (Wheida et al., 2018). According to Sun et al. (2018a), a short-term (1 month) exposure to PM_{2.5} (83 $\mu\text{g m}^{-3}$) and NO₂ (53.3 $\mu\text{g m}^{-3}$) increased the risk of developing acute exacerbation of COPD. Faridi et al. (2018) estimated the long-term effects of PM_{2.5} exposures ranging from 24.7 to 38.8 $\mu\text{g m}^{-3}$ over a 10-year period, which resulted in mortality risks of cerebrovascular diseases – stroke (24.5–36.2%), IHD (19.8–24.1%), and COPD (10.7–15.3%).

7.4. Morbidities

Morbidities due to ambient air pollution are another health outcome, which have not been well investigated from oil industries. Morbidities from air pollutants (e.g., SO₂, NO₂, PM_{2.5}, and PM₁₀) have been reported to be causative factors of hospital admissions for cardiovascular and respiratory diseases, working days lost, RADs, minor restricted activity days (MRADs), and emergency urgent care visitations (Ostro, 2004; WHO, 2016, 2018). Several studies estimated various morbidity cases from some selected ambient air pollutants (mostly on PMs, SO₂, and NO₂) (Belleudi et al., 2010; Dominici et al., 2006; Ghzikali et al., 2015). Although these morbidity cases were investigated in a typical urban environment, they could be important in evaluating similar health effects in refineries and petrochemical industries, where such studies are extremely limited. Capraz et al. (2017) observed very high association of hospital admissions from respiratory diseases due to multiple pollutants exposures. For example, the excess risk at Lag₄ due to PM_{2.5} inhalation was 1.5 (95% CI: 1.09–1.99), NO₂ at Lag₄ was 1.27 (95% CI: 1.02–1.53) and PM₁₀ at Lag₀ was 0.61 (95% CI: 0.33–0.89), when the pollutants levels were above 10 $\mu\text{g m}^{-3}$. Even in the urban environment, few studies have focused on IHD related hospital admissions. Tam et al. (2015) reported the relative risks (RRs) of SO₂, NO₂, PM_{2.5}, PM₁₀ and O₃ to be 1.006–1.021 for combined pollutant model for concentrations above 10 $\mu\text{g m}^{-3}$. However, according to Khaniabadi et al. (2017b), for annual emissions exceeding 10 $\mu\text{g m}^{-3}$, even a normal inhaled air could lead to 20 and 51 cardiovascular and respiratory disease hospital admissions, respectively.

8. Current air pollution control technologies

Application of air pollutant control strategies is one of the measures of improving the human health and wellbeing from the emissions of harmful ambient air pollutants in close proximity to the oil-industry areas (Hasheminasab et al., 2018). There are a number of conventional point source pollution control technologies for some common pollutants such as combustion of low sulfur-fuels, pretreatment of feedstock for sulfur removal, and flue gas desulfur-

ization for SO₂ (Amiry et al., 2008). NO₂ emissions are controlled by reducing the content of elemental nitrogen in crude oil under optimal combustion process (Amiry et al., 2008). PMs are controlled under highly efficient fuel oil combustion. Improvement of atomization and efficient air–fuel mixing are also alternative measures of reducing PM emissions (Amiry et al., 2008). These conventional air pollution control technologies need further improvement and development.

Applications of state-of-the-art efficient technologies can improve petrochemical industry emissions to reduce human exposures and avoid the degradation of the ecosystem (Bosco et al., 2005). Table 6 summarizes new and promising air pollution control technologies of some selected pollutants that may offer an opportunity to effectively control ambient air pollutants from oil industries compared to the conventional methods. With respect to Table 6, most of the SO₂ and NOx removal efficiency via various sources of emissions (i.e. stacks and fluid catalytic cracking units) are within 90–100%. These promising technologies are highly efficient compared to selective catalytic reduction equipped with NOx burner technology with 70–90% reduction (Baukal et al., 2004). Plume nucleation technology could achieve about 30% emissions reduction of SO₂, but most of the aforementioned new technologies might achieve higher reduction rates by about 90–100% (Lonsdale et al., 2012).

9. Knowledge gaps and challenges

Increasing urbanization and megacities development have augmented the number and capacity of oil-based industries to meet the energy demands. As discussed earlier, energy generation through fossil fuels has released a wide-range of ambient acidic gases, PM and trace metals into the environment. Such a huge amount of the ambient air pollutants has been exposed to human populations and the ecosystem through activities such as exploration, production, transportation, and consumption. Further, energy generation from the alternative resources is not able to cover the global demands. With the global efforts to improve human health though exposure to cleaner ambient air, as envisioned in objective number III of United Nations Sustainable Development Goals, it is important to highlight that air quality objectives are not only focused on the urban settings but also on other industries which are the major contributor to air pollutions (Takian and Akbari-Sari, 2016). Achieving high air quality requires trusted measurements, emission inventories and human health impact assessment data, which serve as the basis of emissions control strategies, policy actions and human health impact measurements. To reduce air pollutant emissions from the oil industries and their associated mortalities and morbidities, the following research subjects needs to be properly addressed:

Table 6

New emission control technologies for some common ambient air pollutants from oil industries.

Air Pollution control Technology	Target Pollutant (s)	Mechanism	Efficiency	Demerits	References
Fenton reaction	SO ₂ , NO	Production of hydroxyl radical with Ferric Sulfate	99.8% for SO ₂ 92.5% for NO	Removals were inhibited by liquid, temperature and H ₂ O ₂ /H ₂ O concentrations	Wu et al. (2018)
MnO _x /TiO ₂ catalysis reaction	NO, Hg°	Sole gel method with simultaneous removal of NO and Hg°	Good removal	Lower efficiency occurred in combustion flue gas and also when space velocity was >50,000 h ⁻¹	Zhang et al. (2017a)
Rice straw chars/Ultrasound Enhancement	Hg°	Ultrasound assisted impregnation procedure	95.3% removals were achieved	Hg° removal efficiency were inhibited by H ₂ O and SO ₂	Xu et al. (2018)
Ultrasonic/Fe ²⁺ coated system	SO ₂ , NO	Mass transfer and chemical reactivity	100% for SO ₂ Good removal of NO	Lower removal rate occurred when ultrasound was at 40 kHz	Liu et al. (2018c)
In-situ Fenton	NO	Oxidation of free radicals (-OH, HO ₂ ·)	Maximum of 90.1% removals	Oxidation efficiency of NO reduces above 600 mL/min, 3 and 0.05 for gas flow rate, pH and Fe ²⁺ /H ₂ O ₂ molar ratio, respectively	Yuan et al. (2018)
Wet scrubber/Sea water electrolysis	NOx, SO ₂	Semi-continuous bubble column reactor approach	92% for NOx	Increasing gas flow rate decreases the removals of NOx and SO ₂	Yang et al. (2018a)
Red mud/Potassium halides impregnation	Hg°	Pseudo-second order kinetic model	100% for SO ₂ 89.6–94.3% removals	SO ₂ concentration reduces Hg° removal efficiency	Yang et al. (2018b)
Vacuum Ultraviolet light-Ultrasound Reactor	NO	Vacuum Ultraviolet Light-Ultrasound Chlorine System based on oxidation of hydroxyl radical and ozone	Complete removal of NO	Removal of NO was inhibited when CO ₂ , NO and SO ₂ increases in concentration	Liu et al. (2018d)
Co-activated ozone oxidation system	Hg°	Ozone activation and free radicals production	68.1–89.9% efficiency	Hg° removals are inhibited with increase pH levels and SO ₂ and Hg° inlet concentrations	Liu and Wang (2018)
Vaporized Composite Absorbent	SO ₂ , NO, Hg°	Pre-oxidation of Hg, NO via vaporized Fenton-complex oxidant	100% for SO ₂ 81% for NO 91% for Hg°	Removal of Hg° is only effective when SO ₂ concentrations are high	Zhao et al. (2017)
Lignin-Waste egg shell Hybrid adsorbent	SO ₂	Carbonization of liquid lignin and egg shell	Excellent SO ₂ removal	Adsorbents prepared by egg shell alone showed lower SO ₂ removals compared to hybrid porous carbon	Sun et al. (2018b)
Electron Beam and Wet-Scrubber	NOx, SO ₂	Electron Beam post gas irradiation	84% SO ₂ , 49% NOx removal	Higher inlet NO concentrations decrease the removal efficiency of NOx	Chmielewski et al. (2018)
Polymeric adsorbent with hydro-treatment	H ₂ S, N	Charge transfer complex formation and Taguchi Orthogonal array	94.3% S and 63.3% N	S and N removals are effective when hydrodesulfurization and hydrodenitrogenation are improved	Misra et al. (2018)
Selective catalytic reduction	NO, Hg°	Oxidation of NO, Hg° with Nb-modified MnTiO _x catalyst under 200–300 °C	> 95% removals for NO and Hg°	NH ₃ was found to inhibit Hg° oxidation	Liu et al. (2019)
Ultrathin structural BiOBr/BiOI and BiOBr/BiOI-U photocatalysis	NO	Non-selective oxidation reaction followed by adsorption of surface oxygen vacancies of NO ₃	Showed good removal	BiOBr/BiOI is ineffective in NO removal compared to BiOBr/BiOI-U	Shi et al. (2019)
Spraying reactor of Fenton Reagent	H ₂ S	Hydroxyl radical (-OH) removal and hydrolysis of H ₂ O ₂ concentration	34–100% removal rates	Efficiency of H ₂ S removals reduces with increasing H ₂ S concentrations	Wang et al. (2019)
Fixed-bed reaction	NO	Catalytic decomposition of H ₂ O ₂ and Haber-Weiss mechanisms	54–74%	At a higher catalytic temperature of > 180 °C, NO removals decreases	Wu et al. (2019)

- AQMS should be implemented to monitor emissions specific petroleum industrial areas in order to improve the quality of the data other than measuring air pollutants from other sources (traffic, other industries, etc.). Further, the application of satellites-based land use regression (LUR) models could be an alternative approach of monitoring emissions from sources within various receptors.
- Intensive research is needed to focus on UFP and Nano-particle emissions from the industries as they may pose more serious human health effects compared to conventional pollutants.
- Trace metal bound-PM and -UFP emissions should be quantified for their toxicological and epidemiological impacts to the exposed population in comparison with dust and carbonaceous based PM and UFP.
- HRA studies have mainly focused on single pollutants from oil-based industries; further research should be focused on health effects on combined pollutants to assess their synergic effects.
- There should be a comprehensive HRA research on oil-industry emissions, e.g., in case of COPD and IHD among the exposed populations. Further research is needed to be carried out on the emission and exposure assessment of long-range transportation of oil-industry air pollutants.
- Adequate air quality threshold limits should be developed to cover emissions of ambient trace metals released from oil-industry sources.

10. Concluding remarks

Ambient pollution of acidic gases, PM and trace metals from oil-based industries is a global environmental health problem due to their ubiquitous and persistent nature in the environment. Hence, their presence in the ambient environment is one of the biggest concerns. These pollutants could undergo chemical transformation, nucleation and coagulation to form new chemical species and secondary aerosols. Further, these pollutants enter the human system via inhalation, digestion and dermal contact. Due to their carcinogenicity, respiratory and cardiovascular mortalities potentials, as well as recalcitrant properties of these pollutants, it is important to employ rigorous and sophisticated measuring and monitoring methods in order to ensure accurate estimation of their negative impacts on human health. Several conventional air pollution technologies have been employed in recent years to reduce the emissions of these pollutants from refineries and petrochemical industries to minimize their impacts to the exposed populations. However, companies and government agencies can improve these emission levels with adoption of new and more robust technologies. They will have to invest in research and development to ensure the full applicability of these promising air pollution control technologies and guarantee economic growth. Although there are several knowledge gaps and limitations of the current emissions and exposure assessment of emissions from oil industries, the information reported in this review will draw attention to researchers to fill these knowledge gaps in future.

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Glossary

- $\text{PM}_{2.5}$: PM with aerodynamic diameter of less than 2.5 μm
 PM_{10} : PM with aerodynamic diameter of less than 10 μm